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STUDY OF AN ASYNCHRONOUS LOW DISCHARGE FLOW METER

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ABSTRACT: A system for non-contact measurement of low flow rates of liquid metals using two transformer converters is described. Changes in physical parameters along an elliptical channel in the vicinity of the exciter and sensors are plotted.

Non-contact measurement of low flow rates of liquid metal cool- /806
ants is a timely problem. The diagram of an asynchronous flow meter [1] with two transformer converters, shown in Figure 1, has a criterion of transformation efficiency close to unity. This means that there is a nearly complete transformation of the disturbance of the magnetic flux into a useful signal U_c at the output of the sensor.

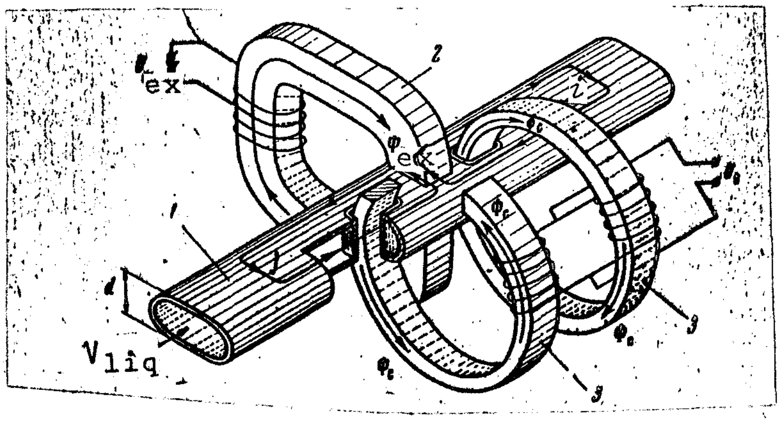

Fig. 1. Diagram of Sensor Design: (1) Channel; (2) Exciter System; (3) Transformer Converters.

A basic component of the sensor is the channel, 1, with an elliptical cross section, in which an electrically conductive fluid moves at a velocity V_{liq}. The channel is located in the gap d of the magnetic circuit of the exciter system. The exciter system, 2, is powered by an ac voltage U_b. The two closed magnetic circuits, 3, of the transformer converters run through the closed rings in the conventional circuit of an asynchronous sensor [2].

As a result of the interaction between the nonuniform magnetic flux Φ_{ex} and the moving conducting fluid, currents are induced in the latter. The current density is proportional to the voltage of the exciting field, as well as the conductivity and flow rate of the fluid.

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*Numbers in the margin indicate pagination in the foreign text.

A clear relationship between the current i and the flow rate Q exists when the first two parameters remain constant. The nature of the current distribution in the volume of liquid around the continuous rings depends on the distribution of the exciting flux Φ_{ex} and the velocity. Theoretical investigations of flow in a nonuniform magnetic field encounter considerable difficulties. Therefore, it is simpler to use the semi-empirical relationships, which give an accuracy sufficient for practical applications. /80

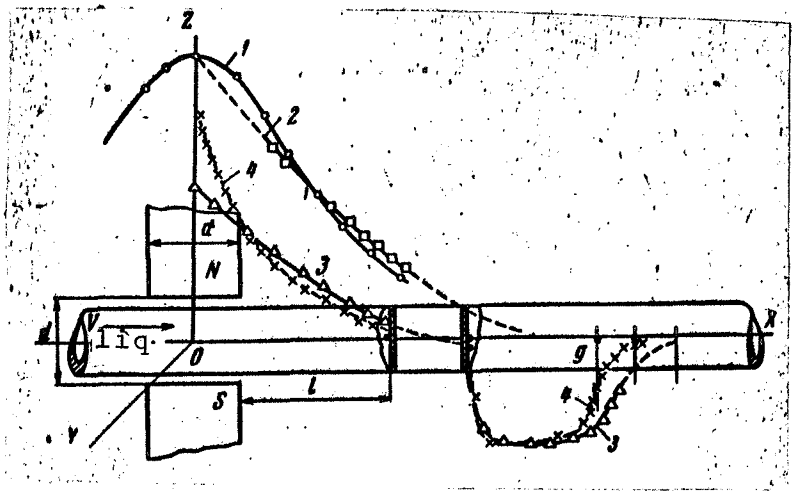

Fig. 2. Changes in Physical Parameters Along the Channel Axis.
(1) Change in Magnetic Induction under Static Conditions;
(2) Change in Magnetic Induction in a Moving Liquid Metal;
(3) Distribution of the Potential of the Electric Field;
(4) Change in Current Density.

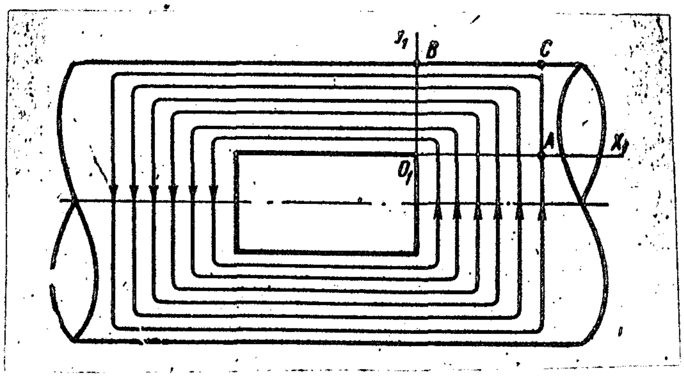

Fig. 3. Idealized Current Pattern.

Figure 2 shows the experimental curves (1 and 2, solid segments) for the distribution of magnetic induction along the axis of the channel. The dashed segments represent extrapolated sections. Curve 1 was obtained under static conditions, where $V_{liq} = 0$. The solid segment of Curve 2 characterizes the change in the distribution of the magnetic field produced by the motion of the liquid metal. Curve 2 is close to the exponent, whose shape factor P can be determined by using experimental data. As the measurements show, the magnitude of the magnetic induction at the point $x = 1.5d$, $y = 0$ is about 0.48 of the maximum value of B_0, at the origin of the coordinates.

Consequently, $0.48B_0 = B_0 e^{-P1.5d}$.

$$P = 0.5/d, \quad B = B_0 e^{-0.5x_1/d}.$$

Sounding measurements indicate that the nature of the distribution of the electric field potential ϕ in a liquid metal along the axis of the channel (Curve 3) is similar to the law of distribution of magnetic induction (Curve 2). Therefore we can analogously assume

$$\varphi = \varphi_0 e^{-0.5x/d},$$

where ϕ_0 is the maximum value of the potential at the origin of the coordinates. Knowing the potential distribution, it is easy to determine the vector field of the voltage E and the current density

$$i = \sigma E.$$

Curve 4 in Figure 2 shows the change in density of the induced current along the axis of the channel. The distance l usually is selected according to design considerations within the limits of 1.5 to 2.5d. The point g is located 1.24 to 1.5d from the ring, where the current density along the axis of the channel may be considered constant in an approximation which is sufficient for practical applications. /808

Figure 3 is an idealized pattern of currents occupying the closed ring and the arrangement of the coordinate axes. An investigation of the nature of the potential distribution ϕ in the rectangle O_1ACB, in which the length of side O_1A is equal to the distance from point g (Fig. 2) to the ring, is made under the assumption that sides BC and AC are insulated, and the flow of the current inward through side O_1A and outward through side O_1B is the same. The lengths of the sides are as follows: $O_1A = a$; $O_1B = b$. The problem is one of solving the equation

$$\frac{\partial^2 \varphi}{\partial x_1^2} + \frac{\partial^2 \varphi}{\partial y_1^2} = 0. \tag{1}$$

With the boundary conditions

$$\left.\begin{aligned} \left(\frac{\partial \varphi}{\partial x_1}\right)_{x_1=0} &= \frac{I}{\sigma b}; & \left(\frac{\partial \varphi}{\partial x_1}\right)_{x_1=a} &= 0; \\ \left(\frac{\partial \varphi}{\partial x_1}\right)_{y_1=0} &= -\frac{I}{\sigma a}; & \left(\frac{\partial \varphi}{\partial y_1}\right)_{y_1=b} &= 0. \end{aligned}\right\} \tag{2}$$

where I is the full current and σ is the conductivity of the liquid.

We then multiply (1) by $\frac{2}{a}\cos\frac{k\pi x}{a}dx$, and integrate within the limits from 0 to a. For ϕ' we obtain the equation

$$\frac{d^2\varphi_k'}{dy_1^2}-\left(\frac{k\pi}{a}\right)^2\varphi_k'=\frac{2I}{\sigma ab}, \quad k=0, 1, 2, \ldots \infty. \tag{3}$$

Using the boundary conditions, we obtain:

$$\left(\frac{d\varphi_k'}{dy_1}\right)_{y_1=0}=-\frac{2I}{\sigma a^2}\int_0^a \cos\frac{k\pi x}{a}dx=\begin{cases}-\frac{2I}{\sigma a} & \text{with } k=0\\ 0 & \text{with } k>0\end{cases} \tag{4}$$

$$\left(\frac{d\varphi_k'}{dy_1}\right)_{y_1=b}=0. \tag{5}$$

Integrating (3) under condition (4) and (5), we will have:

$$\left.\begin{aligned}\varphi_0'&=\frac{I}{\sigma ab}(y_1-b)^2+C\\ \varphi_k'&=-\frac{2Ia}{\pi^2\sigma bk^2} \text{ with } k>0\end{aligned}\right\} \tag{6}$$

where C is a constant.

Any sectionally smooth function can be expanded into a Fourier series by cosines:

$$F(x)=\frac{1}{2}a_0+\sum_{k=1}^{\infty}a_k\cos\frac{k\pi x}{a}, \tag{7}$$

where

$$a_k=\frac{2}{a}\int_0^a F(x)\cos\frac{k\pi x}{a}dx, \quad k=0, 1, 2, \ldots \infty \tag{8}$$

or for our case

$$\varphi=\frac{1}{2}\varphi_0'+\sum_{k=1}^{\infty}\varphi_k'\cos k\pi x/a. \tag{9}$$

In accordance with (5), /809

$$\varphi=\frac{1}{2\sigma ab}(y_1-b)^2-\frac{2Ia}{\pi^2\sigma b}\sum_{k=1}^{\infty}\frac{\cos k\pi x/a}{k^2}+C_{k_0} \tag{10}$$

where C_k is a constant (for example, the potential of the external field).

Using a method for improving the convergence of a series of type (10) for solving the first limiting problem for the rectangle [4], we obtain the final expression for the potential:

$$\varphi = \frac{I}{2\sigma ab}[(y_1 - b)^2 - (x - a)^2] + C_k. \tag{11}$$

In designing the channel, the potential distribution and the hydrodynamic characteristics of the flow portion are taken into account.

The use of Permalloy as a magnetically soft material for the closed magnetic conductors allows a considerable decrease in the sensitivity threshold and an increased coefficient of transmission for the measurement device.

Temperature compensation is achieved with the aid of a temperature-correction unit [3]. For this purpose the exciter system is placed in a saturation mode.

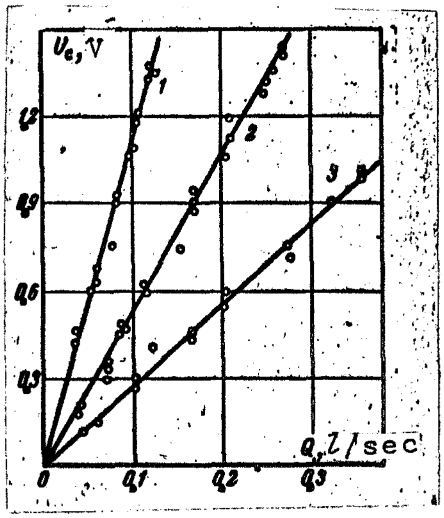

Fig. 4. Experimental Curves. (1) Exciter Current, 0.5 A, Frequency 400 Hz; (2) 2 A, 50 Hz; (3) 1 A, 50 Hz.

A proportional increase in the coefficient of transmission corresponds to an increase in the frequency of the exciting current. Curve 1 in Figure 4 shows the experimental characteristic curve of an experimental form of the sensor, whose exciter current has a frequency of 400 Hz and is equal to 0.5 A. Curves 2 and 3 were obtained at a frequency of 50 Hz and currents of 2 and 1 A, respectively.

An asynchronous system for a low discharge flow meter was tested on a system in which a nearly saturated solution of sodium chloride was circulating. The possibility of non-contact measurement of solutions of electrolytes was confirmed experimentally. The sensitivity threshold of the experimental sample was 0.35 l/sec.

We know that the conductivity of electrolytes is 4-5 orders less than that of liquid metals. Therefore, the sensitivity threshold of a liquid-metal sensor could logically be assumed to be reduced by approximately the same factor. In a liquid-metal system which the author assembled, it was not possible to establish stable flow at flow rates less than 0.03 l/sec.

Experimental studies of a sensor with a differential system of connecting the transformer converters and a differential amplifier (dc) as the first stage of the amplifier unit confirmed the high stability of the measurement system with respect to noise.

The dynamic characteristics of the flow meter as a sensitive element in a feedback circuit for automatic control are determined with the aid of a transmission function of the form

$$\boxed{W = 2KTp/(Tp+1),} \tag{12}$$

where K is the transmission coefficient of the exciter system, $T = L\sigma$ is the time constant of the transformer converter, p is a complex value and L is the inductance of the "input" winding, or the curve of current i.

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